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Energetic and economic analysis of a Brazilian compact cogeneration system: Comparison between natural gas and biogas

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A R T I C L E I N F O

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A B S T R A C T

Cogeneration may be defined as the simultaneous production of electric power and useful heat from the burning of a single fuel. This technique of combined heat and power production has been applied in both the industrial and tertiary sectors. It has been mainly used because of its overall efficiency, and the guarantee of electricity with a low level of environmental impact. The compact cogeneration systems using internal combustion engine as prime movers are thoroughly applied because of the good relationship among cost and benefit obtained in such devices. The cogeneration system of this study consists of an internal combustion engine using natural gas or biogas as fuel, combined with two heat exchangers and an absorption chiller utilising water–ammonia as working mixture. This work presents an energetic and economic comparison between natural gas and biogas as fuel used for the system proposed. The results are useful to identify the feasible applications for this system, such as residential sector in isolated areas, hotels, universities etc.

Contents

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[1] In memoriam.

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1. Introduction

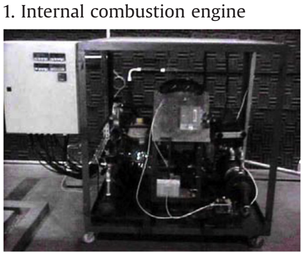
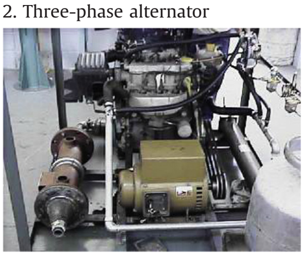
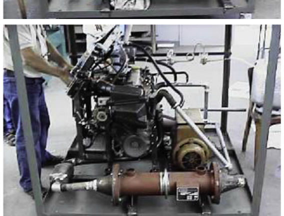
Nowadays, the world economy has experienced a series of crises. In this context and in order to increase their competitiveness, companies are studying a way to reduce their production costs.

It is in this context that cogeneration is presented as an alternative technology very useful. Indeed, cogeneration systems are not characterized only by its energy advantages and environmental preserving, but also for being investments that come with high profitability.

Cogeneration is a technology already used since the last two decades of the XIX century and in the beginning of the XXI century its participation of this technology accounted for 60% of industrial electricity demand in the United States.

Many processes in the chemical, pulp and paper, food and many others, require energy in the form of steam and electricity. When there is simultaneous generation of heat and mechanical or electrical power in industrial plants, it uses the term cogeneration. When is the residential sector, commercial and governmental uses this simultaneous generation, it is customary to use the term integrated energy systems, while for the recovery of residual flows thermoelectric facilities for heating purposes, it is used the term warming district [1].

Table 1
Cogeneration compact system data.

1. Internal combustion engine 	Type: GM Corsa, 1.0 L “98”, 4 stroke, injection system: MPFI—Delphi, compression ratio: 9.4:1, maximum power: 44 kW, maximum torque: 81 N m, maximum rotation: 6000 rpm
2. Three-phase alternator 	Frequency: 60 Hz, poles number: 4, rotation: 1800 rpm, cosφ: 0.8, power: 12.5 kVA, current at 220 V: 32.8 A
3. Absorption chiller 	Refrigerating capacity: 17.4 kW, (5 TR), current drain: 1275 W, Dimensions:—depth: 850 mm, height: 1190 mm, width: 1230 mm
4. Heat exchangers 	Type: shell and tube (water/water), tubes number: 40, tubes diameter: 9.525 mm, tubes thickness: 0.79 mm, tubes distance: 12.5 mm, baffles number: 7, baffles' cut: 30%
	Type: shell and tube (gas/water), tubes number: 76, tubes diameter: 9.525 mm, tubes thickness: 0.79 mm, tubes distance: 12.5 mm, baffles number: 3, baffles' cut: 27%

Nomenclature

C_{cold}	cold water production cost [US$/kWh]
C_{el}	electricity production cost [US$/kWh]
C_{fuel}	fuel cost [US$/kWh]
C_{hot}	hot water production cost [US$/kWh]
$C_{MAN(PM+G)}$	maintenance cost for the prime mover and generator [US$/kWh]
$C_{MAN(HE)}$	maintenance cost for heat exchangers [US$/kWh]
$C_{MAN(AM)}$	maintenance cost for absorption machine [US$/kWh]
COP	coefficient of performance [dimensionless]
C_p	specific heat at constant pressure [kJ/kg K]
$C_{p\ gases}$	specific heat at constant pressure of the exhaust gases [kJ/kg K]
d	density [kg/m^3]
E_{cold}	cold water produced [kW]
E_{el}	electricity produced [kW]
E_{hot}	hot water produced [kW]
f	annuity factor [1/years]
H	equivalent utilization period [h/year]
I_{AM}	absorption machine capital cost [US$/kW]
I_{HE}	heat exchangers capital cost [US$/kW]
I_{PM+G}	prime mover and generator capital cost [US$/kW]
k	payback period [years] (It reflects the length of time required for a project to return its investment through the net income derived or net savings realized)
LHV	lower heating value [kJ/kg or kJ/Nm^3]
m	mass flow [kg/s]
m_{fuel}	fuel consumption [kg/s or m^3/s]
m_{gases}	exhaust gases mass [kg/s]
PF_{cold}	pondering factor for cold water [dimensionless]
PF_{el}	pondering factor for electric energy [dimensionless]
PF_{hot}	pondering factor for hot water [dimensionless]
Q	heat flow [kW]
Q_{abs}	heat flux used by the absorption machine to produce cold water [kW]
Q_{cool}	heat flux from engine cooling system [kW]
Q_{ex}	heat flux from exhaust gases [kW]
Q_{fuel}	heat flow from the combustion [kW]
Q_{loss}	mechanic and radioactive losses [kW]
Q_{rec}	heat flux retrieved from exhaust gases [kW]
r	annual interest rate [%] (=4%; 8%; 12%)
V	volume [m^3]
W_{out}	output power [kW]
ΔT	temperature difference [°C or K]
η_{biogas}	thermal efficiency of the engine operating with biogas
$\eta_{gasoline}$	thermal efficiency of the engine operating with gasoline
$\eta_{natural\_gas}$	thermal efficiency of the engine operating with natural gas

Due to rising costs of energy inputs or fuels used to generate steam or electricity purchased from utilities, industries are in search of higher energy utilization. Energy costs may limit the development of the industry, so there is a constant need to revise the traditional stance on energy, where to get it and how to use it.

Several works have presented compact cogeneration systems based on internal combustion engine associated to downdraft biomass gasification systems as a solution for portable power applications on agricultural farms and in rural areas [2–5].

Also exergo-economic analysis of cogeneration systems for application in tertiary sector [6–8] and residential buildings [9–10] have been studied.

Recently in Brazil, several projects that aim the use of bio-fuels were implanted. In a station of effluents from the city of São Paulo, biogas has been used to generate electricity with internal combustion engines and with a 30 kW micro gas turbine. A comparison between the emissions released from both technologies is also carried out [11].

Karellas et al. [12] developed an investment decision tool to be applied in the production of biogas from agricultural waste, informing how to dimension the digester, the expected biogas production, the costs involved and its amortization.

The economic feasibility of this technology in a rural property, even without receiving carbon credits, was demonstrated by [13] where the performance of an engine generator set of 100 kVA was evaluated. The rural property use two biodigesters to produce biogas from swine waste.

Recent technologies of combined cooling, heating and power generation as organic Rankine systems, fuel cells and liquid desiccant cooling were presented in [14], with a review of

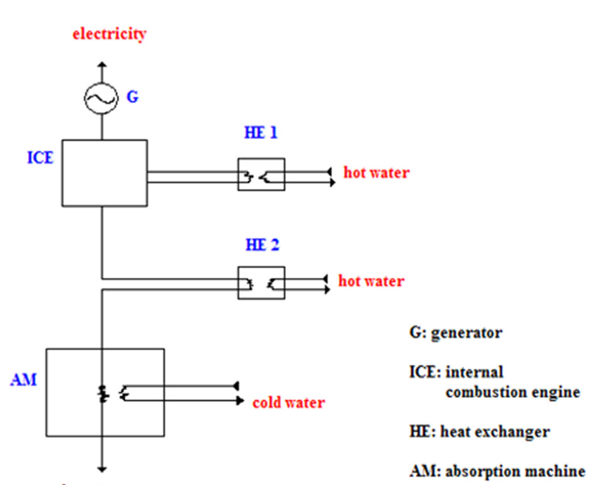


Fig. 1. Compact cogeneration system scheme.

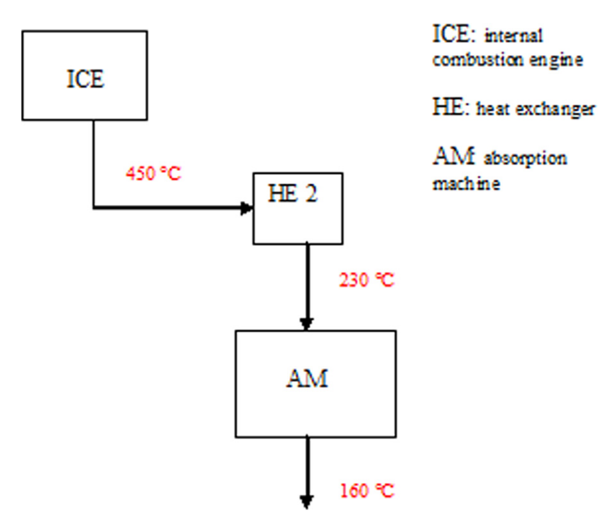


Fig. 2. Exhaust gases temperature levels using natural gas.

tri-generation well-established systems such as internal combustion engines, gas turbines and absorption cooling.

This work presents an energetic and economic comparison between natural gas and biogas as fuel used for the system proposed.

2. Energetic analysis of the Brazilian compact cogeneration system

2.1. Engine design analysis

The compact cogeneration system studied in this work is a “stand alone” system, not connected to the grid. This is especially useful in countries like Brazil, where there is not the possibility to connect the whole territory to the national grid, due to its vastness. This system is constituted by a little internal combustion engine (GM Corsa 1.0 L MPFI), associated with an electrical generator and two heat exchangers, and coupled with an absorption chiller (5 TR, Robur). The engine can use gasoline, LPG, natural gas or biogas as fuel because a special fuel system (Rodagas) and it generates an output power of about 13 kW that drives the electrical generator with an efficiency of 97%. The jacket water of the engine has a heat exchanger instead of the original heat radiator, from which the water thermal energy is used for hot water production (temperature of about 60 °C). The exhaust gases are directed in a second heat exchanger in which their temperature is reduced to a suitable level to run the absorption chiller. Before going to the second heat exchanger the gases pass through a catalyst in order to reduce pollution emission. The heat expelled in the reducing temperature process is used for hot water production, in addition to that produced in the engine cooling system (jacket water system).

The absorption system works with a water–ammonia mixture and it produces cold water at 7 °C, which can be used in human consumption water machines or fan coils.

The electrical power from the generator is dissipated in an electrical resistance bench placed in a tank with water.

The absorption system COP is in the order of 0.58 and the internal combustion engine works with an air/fuel ratio of about 12, depending on the fuel type.

Table 1 shows the cogeneration system data: engine, absorption machine, electric generator and heat exchangers.

The three-phase alternator regulates its voltage with a compound system which guarantees a good regulation independent of the applied charge. The regulation circuit alimentation is done by an auxiliary coil placed in the stator, in phase with the rotating armature.

In the refrigeration system a water–ammonia mixture heats up itself in a generator, where ammonia evaporates and parts from water. The dry saturated ammonia vapour is transferred to a condenser where it gets cold with air at ambient temperature and it turns back liquid (these two first steps of the process have the same function than the compressor in the common air conditioning systems).

A rectifier is placed between the generator and the condenser. Its function is to remove any trace of water from the refrigerant before it enters the condenser. The liquid ammonia passes now through a throttling valve, where the pressure is reduced. Then it flows to an evaporator, picking up heat from the surroundings and leaving as a saturated vapour. The cold ammonia vapour arrives now in the absorber, where it mixes with a hot aqueous solution and it's condensed and absorbed. In this moment it happens the absorption process, that gives name to the entire cycle.

For ammonia the heat of reaction is positive, so a heat exchanger must be located in the absorber to cool the hot aqueous solution, improving its absorbing capability and removing the latent heat of condensation and reaction. This aqueous solution, with a high percentage of ammonia in water, leaves the absorber and enters the pump. The final high pressure cool mixture comes back to the generator, where heat is added to part the ammonia from solution. The ammonia leaves as a saturated vapour, and the whole cycle starts again.

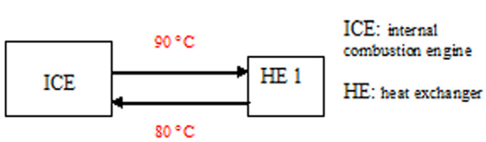


Fig. 3. Cooling water temperature levels using natural gas.

Table 2
The Brazilian natural gas composition.

CH_4	89.35% in V
C_2H_6	8.03% in V
C_3H_8	0.78% in V
C_4H_{10}	0.07% in V
C_5H_{12}	0.01% in V
CO_2	0.48% in V
N_2	1.28% in V

Table 3
Composition after combustion.

H_2O	15.67%
CO_2	8.24%
N_2	72.79%
O_2	3.29%

Table 4
Natural gas engine data.

Engine rotation	1800 rpm
W_{out}	13.2 kW
LHV	37,955.1 kJ/Nm^3
C_p	1.225 kJ/kg K
m_{fuel}	4.81 Nm^3/h
M	0.021136 kg/s

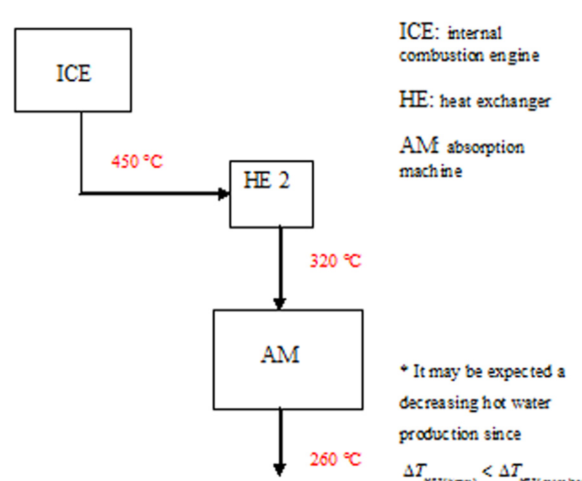


Fig. 4. Exhaust gases temperature levels using biogas.

The heat exchangers are constructed with copper or carbon steel tubes, melted iron covers, carbon steel mirrors. The carbon steel used is DIN 2440. They are tested at a pneumatic pressure of 12 bar in the shell and 6 bar in the tubes, and at a hydrostatic pressure of 25 bar in the shell and 10 bar in the tubes [15].

In Fig. 1, it is shown the compact cogeneration system scheme.

2.2. Energetic analysis

According to [15], Eqs. (1)–(5) can be used for an energetic analysis of the system. Eq. (1) is to evaluate the fuel in the engine, Eq. (2) is to evaluate the exhaust gases and the cooling water in the engine, Eq. (3) is to evaluate the general energetic balance in the engine, and Eqs. (4) and (5) are related to absorption machine.

$$Q_{fuel} = \dot{m}_{fuel} \times \mathrm{LHV} \quad (1)$$

$$Q = \dot{m} \times c_p \times \Delta T \quad (2)$$

$$Q_{fuel} = W_{out} + Q_{cool} + Q_{ex} + Q_{loss} \quad (3)$$

$$Q_{abs} = Q_{rec} \times COP \quad (4)$$

$$Q_{rec} = \dot{m}_{gases} \times c_{p\ gases} \times \Delta T \quad (5)$$

2.3. Natural gas as fuel

Its origins are similar to coal or oil: natural gas is the result of a long decomposition of organic matter in oxygen deficiency, under extreme conditions of pressure and temperature.

Natural gas, as a cleaner burning source of fossil fuel than oil or coal, is now commonly believed to offer part of the solution to climate change and problems associated with poor air quality. Once considered largely a waste product of oil production, natural gas is currently experiencing a huge increase in demand around the world. As a plentiful, economically viable, and less polluting fuel, natural gas makes sense for developing economies looking for new sources of power [16].

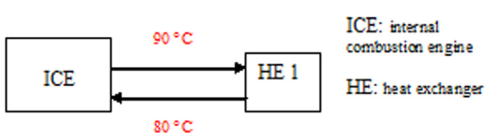


Fig. 5. Cooling water temperature levels using biogas.

Table 5
The Brazilian biogas composition.

CH_4	62.7% in V
N_2	13.4% in V
CO	5% in V
CO_2	2.4% in V
H_2O	2.4% in V
H_2S	14.1% in V

Table 6
Biogas engine data.

Engine rotation	1800 rpm
W_{out}	13.2 kW
LHV	22,600 kJ/N m^3
C_p	1.094 kJ/kg K
m_{fuel}	8.33 N m^3/h
m	0.036359 kg/s

Unlike coal and oil, natural gas has a higher hydrogen/carbon ratio and emits less carbon dioxide for a given quantity of energy consumed. As the cleanest burning fossil fuel, natural gas offers an immediate, cost-effective means to improve air quality. Unlike coal and oil, it releases virtually no particulate matter, which impedes photosynthesis in plants and aggravates heart and lung disease in humans. Particulate matter is also a contributor to smog. The production and combustion of fossil fuels also generates nitrogen and sulphur oxide emissions. Nitrogen oxides result in various environmental impacts—including smog and acid rain. Sulphur oxides are also a primary contributor to acid rain [17].

The Brazilian natural gas industry is relatively small at present compared with its oil sector. Proved reserves, as reported by the Brazilian WEC (World Energy Council) Member Committee, are now the fifth largest in South America [18]. The proved amount of gas in place is reported as 1211 bcm (billion cubic meters), over twice the level notified for the 1998 Survey. Of the latest assessment of proved recoverable reserves, approximately 26% is non-associated with crude oil. Additional recoverable reserves, not classified as proved, are put at just under 173 bcm.

Gross production rose by nearly 90% between 1990 and 1999; over one-third of current output is either re-injected or flared. Marketed production is mostly used as industrial fuel or as feedstock for the production of petrochemicals and fertilizers. As a consequence of Brazil's huge hydro-electric resources, use of natural gas as a power-station fuel has been minimal. The consumption picture will change as imported gas (from Bolivia and Argentina) fuels the large number of gas-fired power plants that are being built in Brazil [19].

This cogeneration system has a good point of operation for an engine rotation of 1800 rpm, which is the generator rotation. An output power of 13.2 kW is fixed. An air excess of 20% is considered in the combustion process. According to [20], $\mathrm{LHV}_{\mathrm{natural\ gas}} = 37{,}955.1$. In Figs. 2 and 3 are shown the working estimated temperatures of exhaust gases and cooling water respectively [21].

2.3.1. Calculation of C_p

In Table 2 is shown the natural gas composition in Brazil [20].

Table 7
Energetic results comparison.

	Natural gas	Biogas
Q_{fuel}	50.71 kW (100%)	52.29 kW (100%)
W_{out}	13.2 kW (26.03%)	13.2 kW (25.24%)
Q_{cool}	14.23 kW (28.06%)	14.23 kW (27.21%)
Q_{ex}	12,77 kW (25.18%)	16.04 kW (30.67%)
Q_{loss}	10.51 kW (20.73%)	8.82 kW (16.88%)

Table 8
Energy balance.

	Natural gas	Biogas
E_{fuel}	50.71 kW (100%)	52.29 kW (100%)
ICE losses	10.51 kW (20.73%)	8.82 kW (16.88%)
E_{el} Generator losses	12.8 kW (25.24%)	12.8 kW (24.48%)
	0.4 kW (0.79%)	0.4 kW (0.76%)
$E_{hot\ water\ from\ cooling\ system}$	12.1 kW (23.86%)	12.1 kW (23.14%)
HE1 losses	2.13 kW (4.2%)	2.13 kW (4.07%)
$E_{hot\ water\ from\ exhaust\ gases}$	1.97 kW (3.88%)	0.38 kW (0.73%)
HE2 losses	1.92 kW (3.79%)	2.41 kW (4.6%)
$E_{cold\ water}$	5.15 kW (10.16%)	7.66 kW (14.65%)
AM losses	3.73 kW (7.35%)	5.59 kW (10.69%)

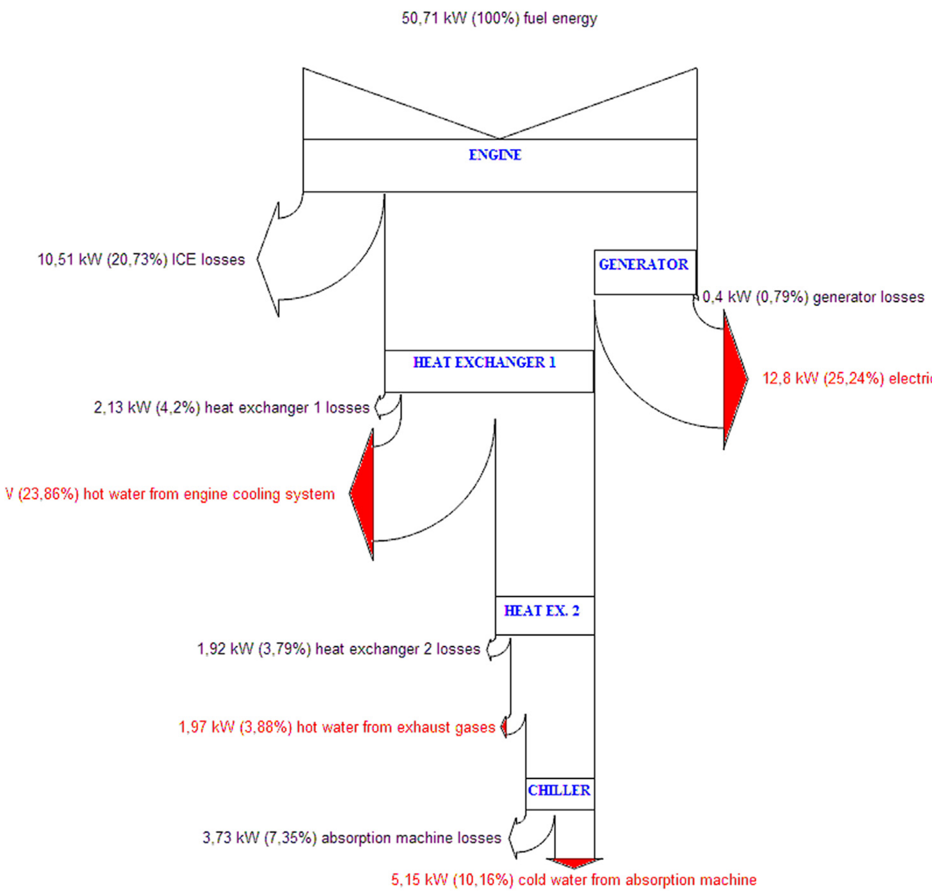


Fig. 6. Sankey diagram of the compact cogeneration system for natural gas fuelled.

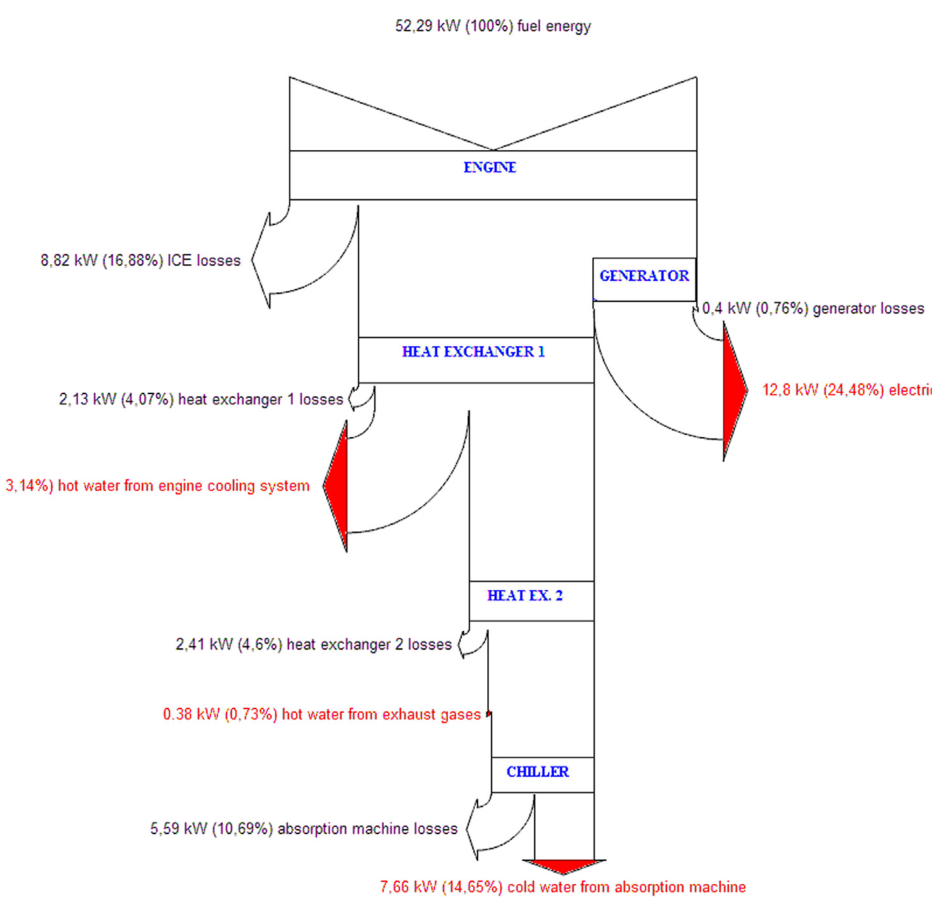


Fig. 7. Sankey diagram of the compact cogeneration system biogas fuelled.

Table 3 shows composition after the combustion with 20% air excess (thermo-chemical balance program NASA SP-293 [22]).

According to [23]:

$$\overline{C}_{p_{(H_2O)}} = 143.05 - 183.54\vartheta^{0.25} + 82.751\vartheta^{0.5} - 3.6989\vartheta \tag{6}$$

$$\overline{C}_{p_{(CO_2)}} = -3.7357 + 30.529\vartheta^{0.5} - 4.1034\vartheta + 0.024198\vartheta^2 \tag{7}$$

$$\overline{C}_{p_{(N_2)}} = 39.06 - 512.79\vartheta^{-1.5} + 1072.7\vartheta^{-2} - 820.4\vartheta^{-3} \tag{8}$$

$$\overline{C}_{p_{(O_2)}} = 37.432 + 0.020102\vartheta^{1.5} - 178.57\vartheta^{-1.5} + 236.88\vartheta^{-2} \tag{9}$$

with

$$\vartheta = \frac{T}{100}[K] \tag{10}$$

and being, according to Fig. 2,

$$T = \frac{T_{input} + T_{output}}{2} = \frac{450 + 230}{2} = 340\ ^\circ C$$

$$T_K = T_{^\circ C} + 273.15 = 340 + 273.15 = 613.15\ K$$

then $\vartheta = 6.1315$ and, considering also the right molecular weight (H_2O: 18, CO_2: 44, N_2: 28, O_2: 32),

$$\overline{C}_{p_{(H_2O)}} = 36.46\,[\mathrm{kJ/kmol\ K}] \rightarrow C_{p_{(H_2O)}} = 2.02\ \ [\mathrm{kJ/kg\ K}]$$

$$\overline{C}_{p_{(CO_2)}} = 47.61\,[\mathrm{kJ/kmol\ K}] \rightarrow C_{p_{(CO_2)}} = 1.08\ \ [\mathrm{kJ/kg\ K}]$$

$$\overline{C}_{p_{(N_2)}} = 30.26\ \ [\mathrm{kJ/kmol\ K}] \rightarrow C_{p_{(N_2)}} = 1.08\ \ [\mathrm{kJ/kg\ K}]$$

$$\overline{C}_{p_{(O_2)}} = 32.28\,[\mathrm{kJ/kmol\ K}] \rightarrow C_{p_{(O_2)}} = 1.01\ \ [\mathrm{kJ/kg\ K}]$$

considering a weight average:

$$C_p = 2.02 \times 0.1567 + 1.08 \times 0.0824 + 1.08 \times 0.7279 + 1.01 \times 0.0329 \cong 1.225\ \ [\mathrm{kJ/kg\ K}]$$

So, $C_{pgases(naturalgas)} = 1.225$ kJ/kg K.

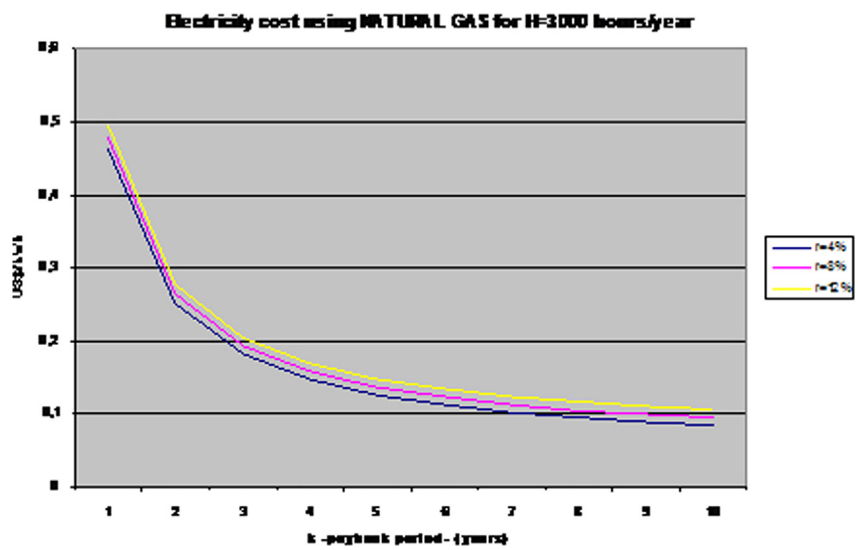


Fig. 8. Electricity cost using natural gas for 3000 h/year.

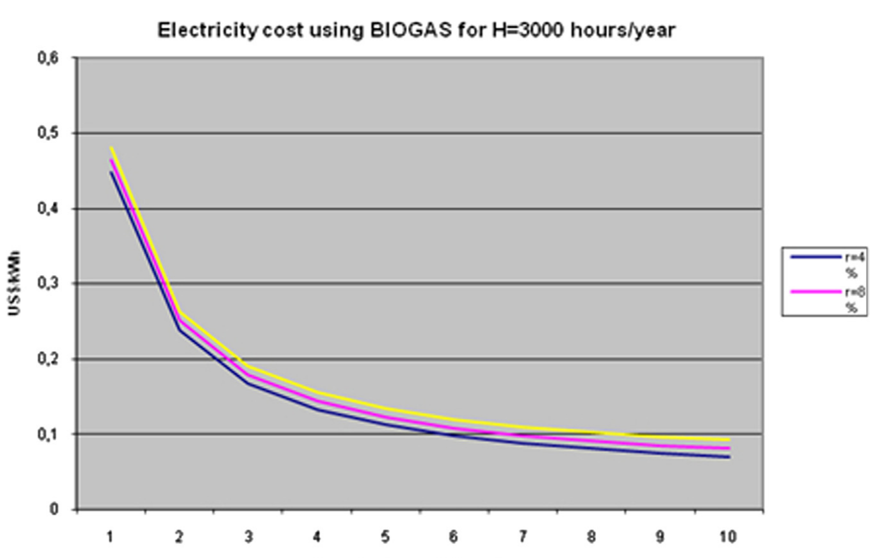


Fig. 9. Electricity cost using biogas for 3000 h/year.

2.3.2. Calculation of m_{fuel}

It can be done an estimation of the engine thermal efficiency, assuming that $\eta_{\text{biogas}} < \eta_{\text{natural\_gas}} < \eta_{\text{gasoline}}$.

Considering $\eta_{biogas} \cong 25\%$ and $\eta_{gasoline} \cong 27\%$ [21]. It may be assumed $\eta_{natural\_gas} \cong 26\%$. It is known that

$$\eta = \frac{W_{out}}{Q_{fuel}} \tag{11}$$

so, also considering Eq. (1),

$$\dot{m}_{fuel(natural\_gas)} = \frac{W_{out}}{\eta_{natural\_gas} \times LHV_{natural\_gas}} = \frac{13.2 \times 3600}{0.26 \times 37,955.1} = 4.81\ [\text{N m}^3/h].$$

2.3.3. Calculation of m

It is known that:

$$m = d \times V$$

$$\dot{m}_{natural\_gas} = \dot{m}_{fuel} \times d_{natural\_gas} + \dot{m}_{air} \times d_{air} \tag{12}$$

with: $m_{\text{fuel}} = 4.81\ \text{N m}^3/\text{h}$, $d_{\text{natural\_gas}} = 0.7\ \text{kg/m}^3$ [24], $m_{\text{air}} = 57.72\ \text{N m}^3/\text{h}$ (air/fuel ratio = 12), $d_{\text{air}} = 1.19\ \text{kg/m}^3$, and considering $1\ \text{N m}^3 = 1.056\ \text{m}^3$.

So, for Eq. (12):

$$\dot{m}_{natural\_gas} = 1.056 \times 4.81 \times 0.7 + 1.056 \times 57.72 \times 1.19 = 76.0888\ [\text{kg}/h] \rightarrow 0.021136\ [\text{kg}/s].$$

2.3.4. Results

Table 4 relates data from an engine that it uses natural gas as fuel.

According to these data, considering Eqs. (1), (2), (4) and (5), and fixing $m_{\text{water}} = 0.340$ kg/s and $C_{p\ \text{water}} = 4.186$ kJ/kg °C [21], it can be written as

- $Q_{fuel} = 4.81 \times 37,955.1 = 182,564.031\ [\text{kJ}/h] \rightarrow 50.71\ [kW]$
- $Q_{ex} = 0.021136 \times 1.225 \times 493.15 = 12.77\ [kW]$
- $Q_{cool} = 0.340 \times 4.186 \times 10 = 14.23\ [kW]$

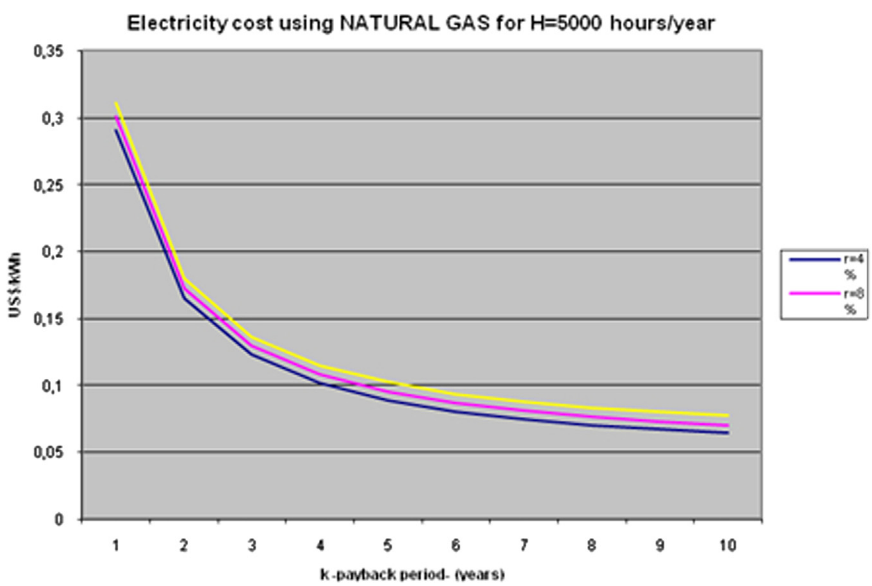


Fig. 10. Electricity cost using natural gas for 5000 h/year.

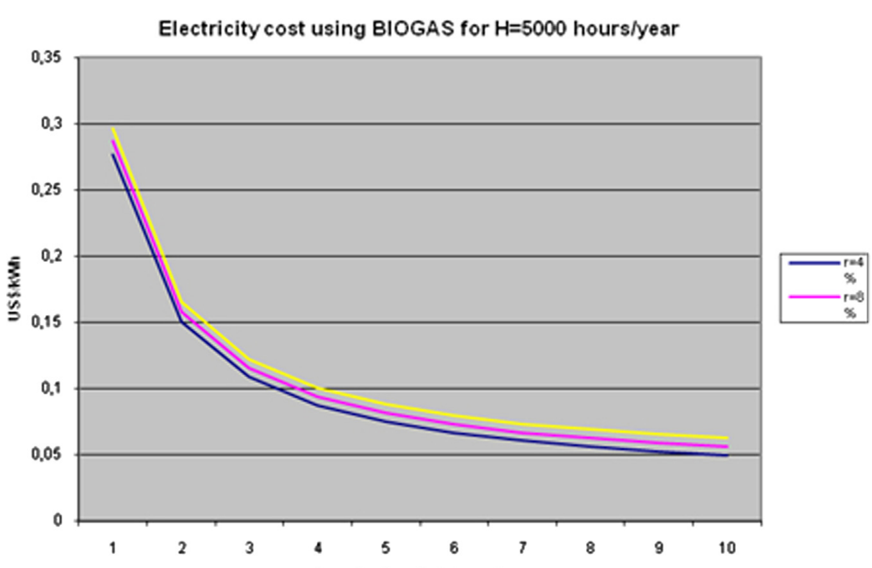


Fig. 11. Electricity cost using biogas for 5000 h/year.

- $Q_{rec} = 0.021136 \times 1.225 \times 343.15 = 8.88\ [kW]$
- $Q_{abs} = 8.88 \times 0.58 = 5.15\ [kW]$

2.4. Biogas as fuel

Another possible alternative engine fuel is biogas, which is impure methane evolved during the decay of organic matter, and it is a sterile, innocuous, scentless (when purified, otherwise in its natural state it has sulfidric gas scent) product. It has a relatively high availability but is usually of low enthalpy of combustion. The two most common sources of biogas are landfill gas and digester gas, both of which are by-products of anaerobic decomposition of organic matter and are primarily composed of methane (CH_4) and carbon dioxide (CO_2), other than some impurities like hydrogen, sulfurated hydrogen, water vapour, ammonia, nitrogen. Landfill gas is produced during the decomposition of organic matter in sanitary landfills. Digester gas is produced at sewage treatment plants during the treatment of municipal and industrial sewage.

Sulfurated hydrogen (H_2S) is formed during the process of anaerobic fermentation of the sewages, accordingly the produced biogas has a high percentage of this mixture that makes it very corrosive. Therefore it is preferable, whereas possible, the use of materials not vulnerable by sulfurated hydrogen, like stainless steel and plastics; the carbon steel has to be protected with adequate layers of epossidic varnish. It must be avoided also the use of aluminium alloys, copper and unprotected iron.

In industrial sector the biodigestion process introduces greater potentialities and biogas may be used as efficient and economic alternative. Among the more suitable industrial activities for the use of biodigestion as fuel generator and as fertilizer producers there are the garbage antipollution treatments, the dairies, slaughter houses, alcohol's distilleries, sugar factories, breedings and the whole agricultural activity.

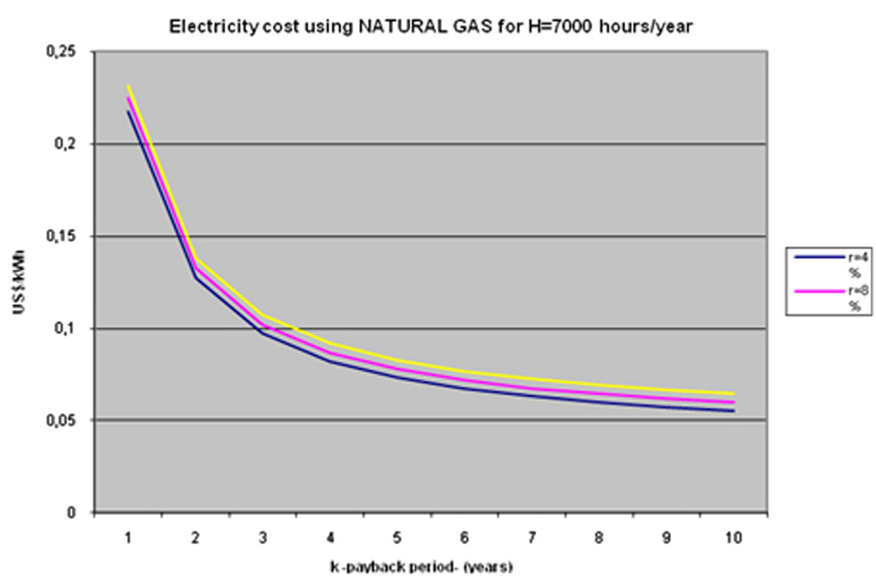


Fig. 12. Electricity cost using natural gas for 7000 h/year.

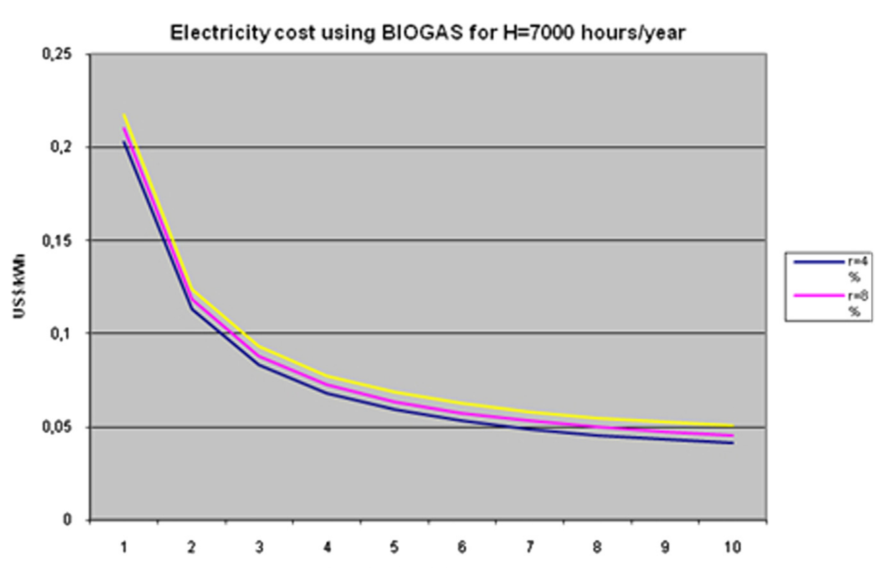


Fig. 13. Electricity cost using biogas for 7000 h/year.

The present work exploits the biogas produced in the anaerobic reactor of a dairy product effluent treating station placed in Vale do Paraiba, Sao Paulo, Brazil.

Engines developed for commercial operation with natural gas can also be used for biogas. Other than somewhat increased frequency of oil changes and a particular attention to possible corrosions caused by sulfurated hydrogen, there are no major operating difficulties encountered [25].

This cogeneration system has a good point of operation for an engine rotation of 1800 rpm, which is the generator rotation. An output power of 13.2 kW is fixed. An air excess of 20% is considered in the combustion process, LHV_{biogas}=22,600 kJ/N m^3 (thermochemical program NASA SP-273) [22].

In Figs. 4 and 5 are shown the working estimated temperatures of exhaust gases and cooling water respectively [21].

2.4.1. Calculation of C_p

In Table 5 is shown the composition of the biogas from a dairy product effluent treating station placed in Vale do Paraiba, Sao Paulo, Brazil [21].

According to [26]:

$$C_p(T) = 1.00454 - \frac{3.33379T}{10^5} + \frac{3.53354T^2}{10^7} - \frac{1.44806T^3}{10^{10}} \tag{13}$$

and being, according to Fig. 4,

$$T = \frac{T_{input} + T_{output}}{2} = \frac{450+320}{2} = 385\ ^\circ C$$

$$T_K = T_{^\circ C} + 273.15 = 385 + 273.15 = 658.15\ K$$

$$C_{pgases(biogas)} = 1.094\ \text{kJ/kg K}$$

2.4.2. Calculation of m_{fuel}

According to some data for a TOTEM 903 cm^3 engine with W_{out}=15 kW [27],

$$\dot{m}_{fuel(biogas)} = 8.33\ [\text{N m}^3/h]$$

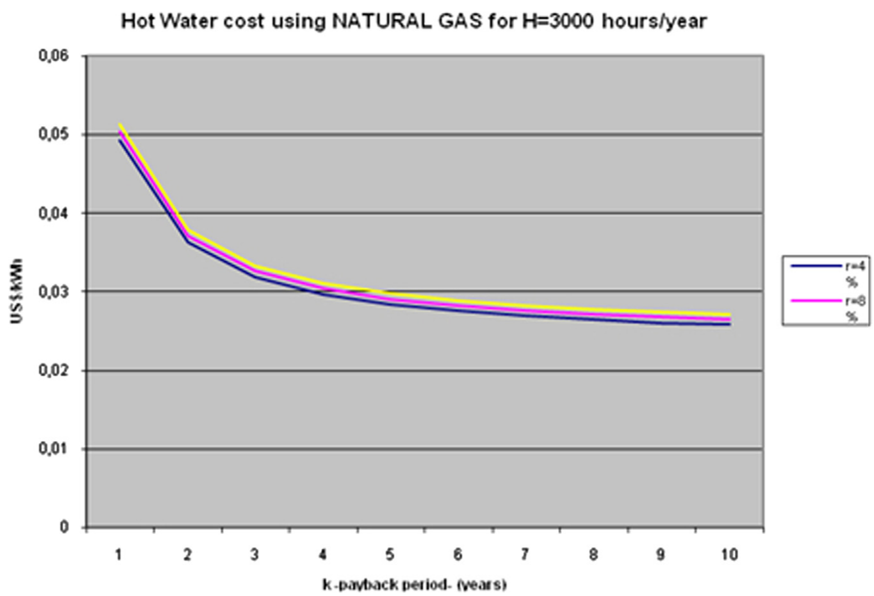


Fig. 14. Hot water cost using natural gas for 3000 h/year.

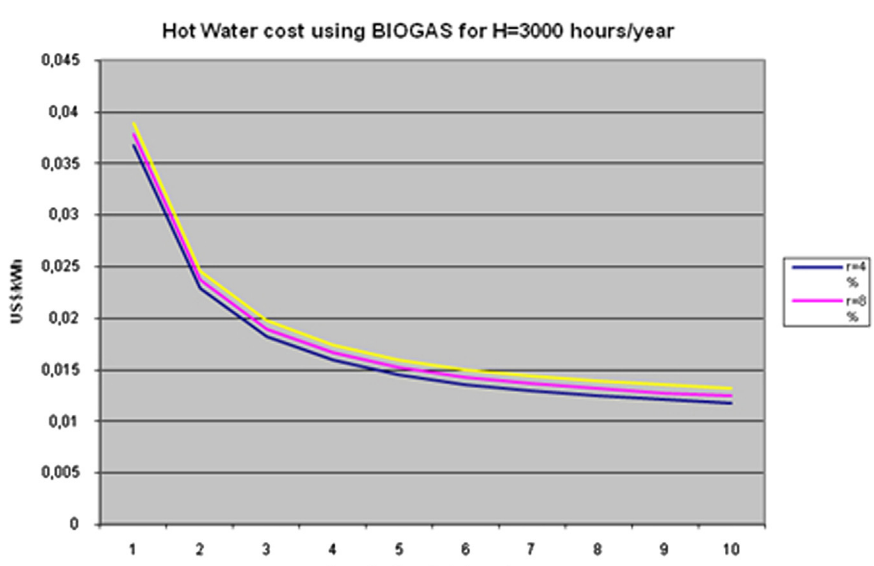


Fig. 15. Hot water cost using biogas for 3000 h/year.

and so, for Eq. (11),

$$\eta_{biogas} = \frac{W_{out}}{\dot{m}_{fuel(biogas)} \times \mathrm{LHV}_{biogas}} = \frac{13.2 \times 3600}{8.33 \times 22,600} = 25.2\%,$$

as expected.

2.4.3. *Calculation of m*

It is known that:

$$m = d \times V$$

$$\dot{m}_{biogas} = \dot{m}_{fuel} \times d_{biogas} + \dot{m}_{air} \times d_{air} \tag{14}$$

with: $m_{fuel}=8.33$ N m^3/h, $d_{biogas}=0.6$ kg/m^3 [24], $m_{air}=57.72$ N m^3/h (air/fuel ratio=12), $d_{air}=1.19$ kg/m^3, and considering 1 N m^3=1.056 m^3.

So, for Eq. (14):

$$\dot{m}_{biogas} = 1.056 \times 8.33 \times 0.6 + 1.056 \times 99.96 \times 1.19 = 130.8916\ [\mathrm{kg}/h] \rightarrow 0.036359\ [\mathrm{kg}/s].$$

2.4.4. *Results*

Table 6 relates data from an engine that it uses biogas as fuel.

According to these data, considering Eqs. (1), (2), (4) and (5), and fixing $m_{water}=0.340$ kg/s and $C_{pwater}=4.186$ kJ/kg °C [15], it can be written:

$$Q_{fuel} = 8.33 \times 22,600 = 188,258\ [\mathrm{kJ}/h] \rightarrow 52.29\ [kW]$$

$$Q_{ex} = 0.036359 \times 1.094 \times 403.15 = 16.04\ [kW]$$

$$Q_{cool} = 0.340 \times 4.186 \times 10 = 14.23\ [kW]$$

$$Q_{rec} = 0.036359 \times 1.094 \times 333.15 = 13.25\ [kW]$$

$$Q_{abs} = 13.25 \times 0.58 = 7.66\ [kW]$$

2.5. *Energetic analysis results*

Table 7 shows a comparison for the engine operating at 1800 rpm with natural gas versus biogas.

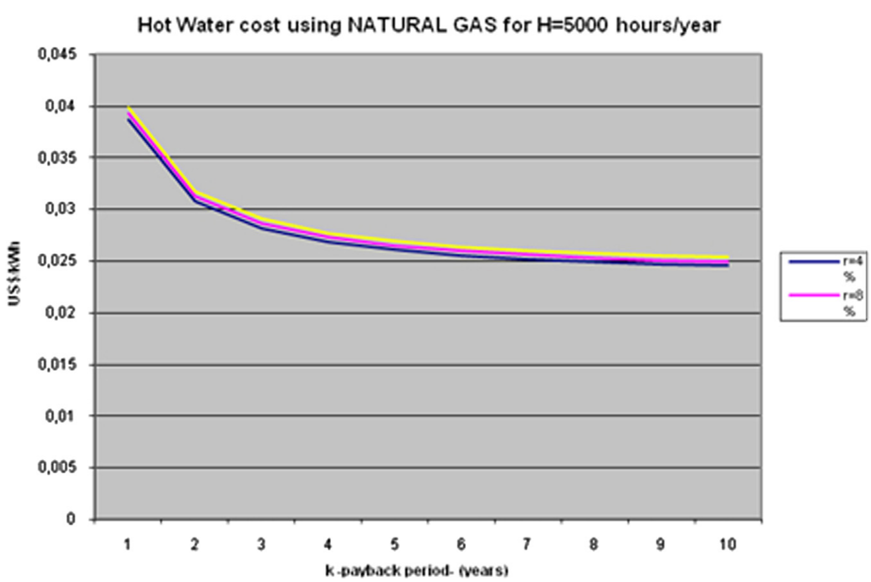


Fig. 16. Hot water cost using natural gas for 5000 h/year.

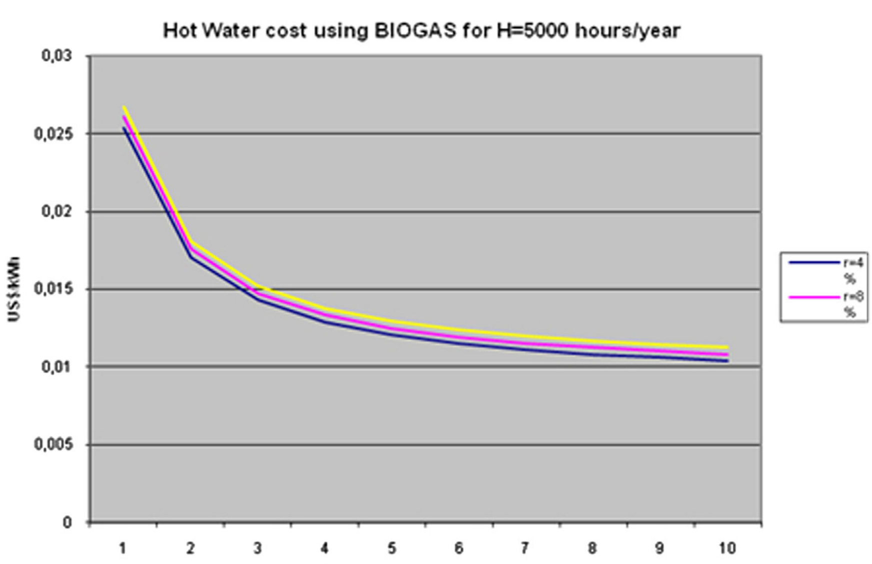


Fig. 17. Hot water cost using biogas for 5000 h/year.

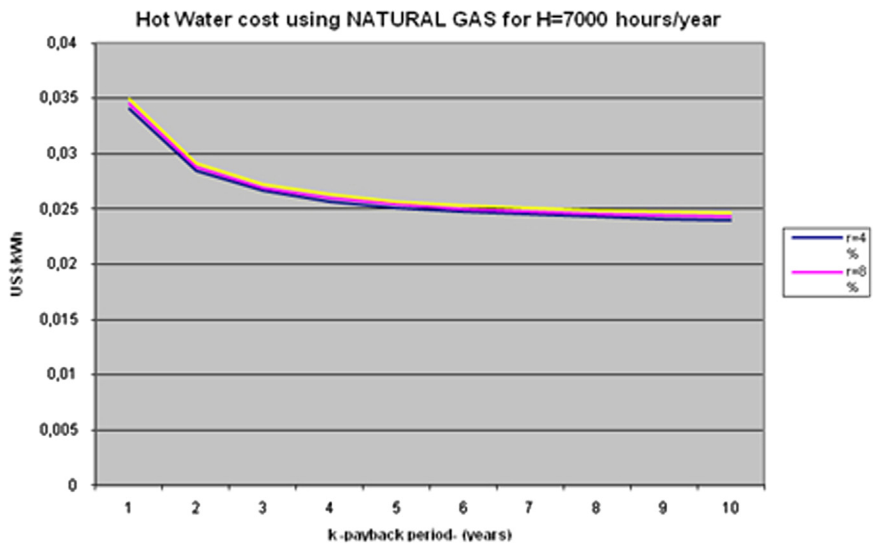


Fig. 18. Hot water cost using natural gas for 7000 h/year.

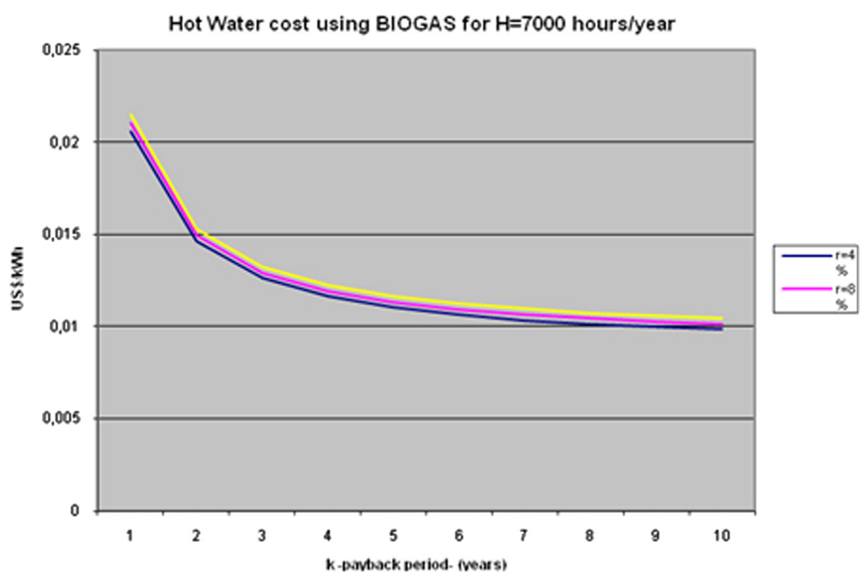


Fig. 19. Hot water cost using biogas for 7000 h/year.

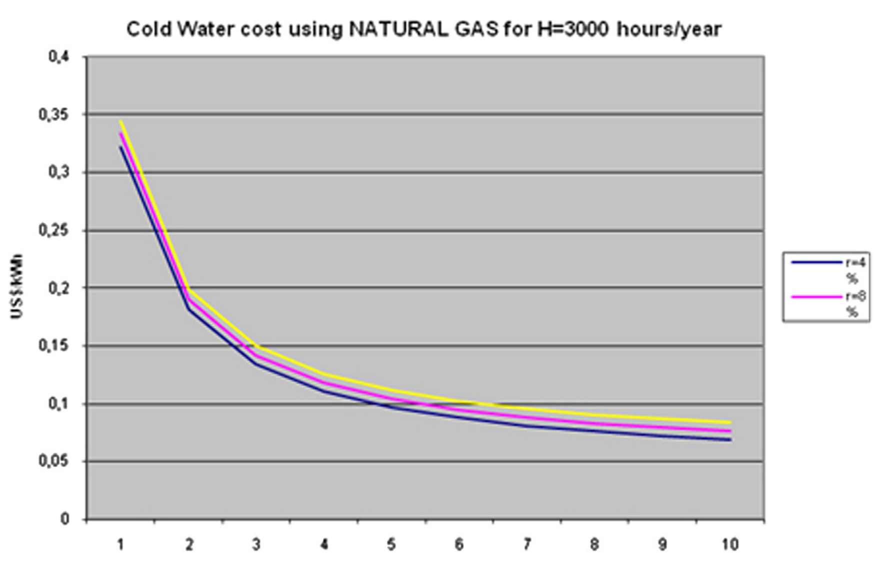


Fig. 20. Cold water cost using natural gas for 3000 h/year.

2.5.1. Energy balance

Considering: $\eta_{heatexchanger}=85\%$, $\eta_{generator}=97\%$, and $COP_{absoption\_machine}=58\%$, values for Table 8 can be evaluated.

Sankey diagrams are specific means to graphically represent energy or mass flows in input/output-processes. The width of the input or output arrows is proportional to the represented energy or material flux. Fig. 6 shows Sankey diagram for natural gas as fuel.

Fig. 7 shows Sankey diagram for biogas as fuel.

3. Economic analysis of the Brazilian compact cogeneration system

3.1. Economic analysis

Cogeneration is a technology that saves fuel resources (primary energy), but it does not necessarily imply any assurance of economic benefits. Irrespective of all its technical merits, the adoption of cogeneration depends on its economic feasibility, which is very much site-specific.

Cogeneration may be considered economical only if the different forms of energy produced have a higher value than the investment and operating costs incurred on the cogeneration facility.

Because of the need to take a relatively medium term view (cogeneration is a relatively expensive capital investment), volatility and uncertainty in energy markets, tariffs or prices may deter potential investors. The economics of cogeneration are sensitive to the level of energy prices, and the differential between the price of the fuel used by the prime mover, and the value of the electricity and heat which is generated.

Following are the major factors that need to be taken into consideration for economic evaluation of this cogeneration project:

1. initial investment;
2. operating and maintenance costs;
3. fuel price.

Adapting the [28] and [29] methods, developed by [27], the relations for costs of electricity, hot water and cold water

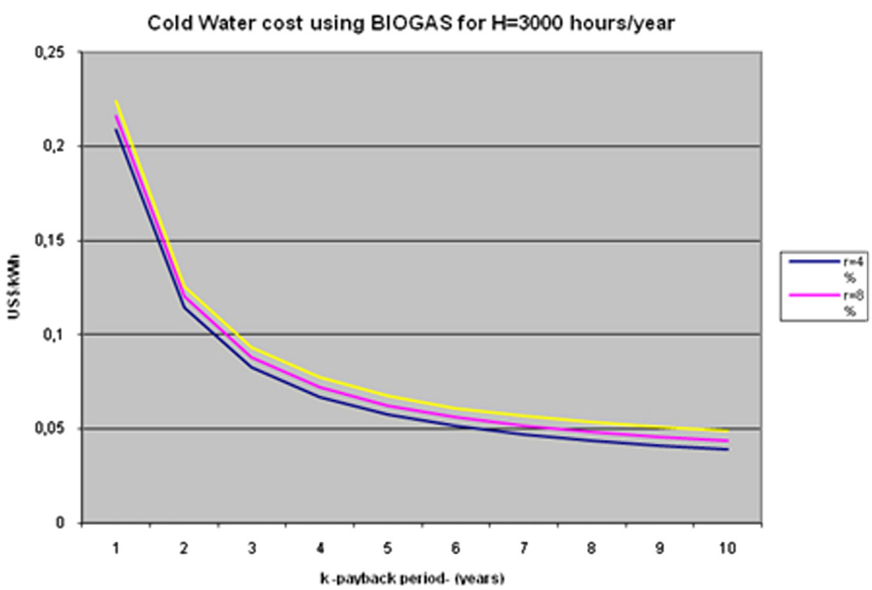


Fig. 21. Cold water cost using biogas for 3000 h/year.

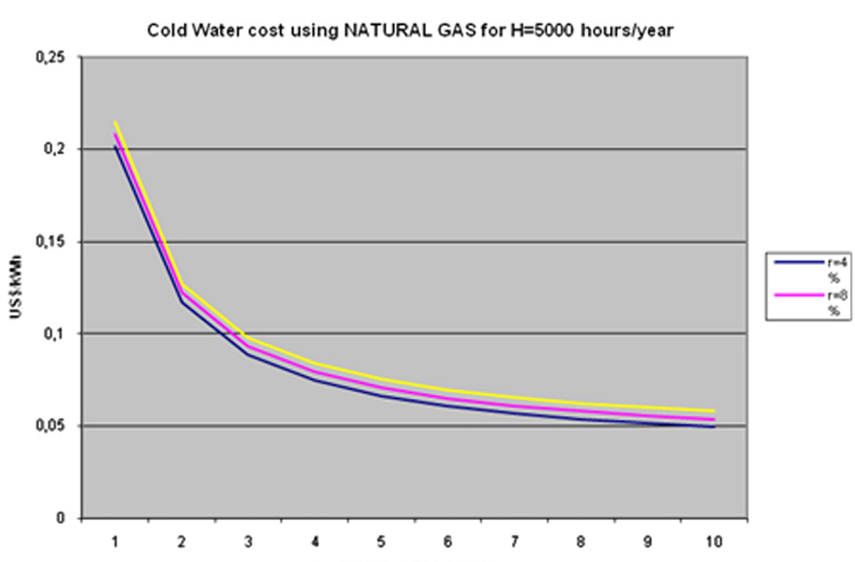


Fig. 22. Cold water cost using natural gas for 5000 h/year.

production may be determined with the following equations:

$$C_{el} = \frac{I_{PM+G} \times f}{H \times E_{el}} + \frac{C_{fuel} \times PF_{el}}{E_{el}} + C_{MAN(PM+G)} \quad (15)$$

$$C_{hot} = \frac{I_{HE} \times f}{H \times E_{hot}} + \frac{C_{fuel} \times PF_{hot}}{E_{hot}} + C_{MAN(HE)} \quad (16)$$

$$C_{cold} = \frac{I_{AM} \times f}{H \times E_{cold}} + \frac{C_{fuel} \times PF_{cold}}{E_{cold}} + C_{MAN(AM)} \quad (17)$$

With, according to the previous values and to [27]:

- $I_{PM+G}=1200$ US$/kW
- $I_{HE}=60$ US$/kW
- $I_{AM}=3000(E_{cold}[TR]/3)^{0.69}$ [29]
- $E_{el\ (NATURAL\ GAS)}=12.8$ kW
- $E_{el\ (BIOGAS)}=12.8$ kW
- $E_{hot\ (NATURAL\ GAS)}=14.07$ kW
- $E_{hot\ (BIOGAS)}=12.48$ kW
- $E_{cold\ (NATURAL\ GAS)}=5.15$ kW
- $E_{cold\ (BIOGAS)}=7.66$ kW
- $H=3000$ h/year; 5000 h/year; 7000 h/year
- $C_{fuel\ (NATURAL\ GAS)}=0.013$ US$/kWh
- $C_{fuel\ (BIOGAS)}=0.004$ US$/kWh
- $C_{MAN(PM+G)}=0.0130$ US$/kWh
- $C_{MAN(HE)}=0.002$ US$/kWh
- $C_{MAN(AM)}=300(E_{cold}[TR]/3)^{0.5}$ [29]
- $PF_{el\ (NATURAL\ GAS)}=E_{el}/(E_{el}+E_{hot}+E_{cold})=0.4$
- $PF_{el\ (BIOGAS)}=E_{el}/(E_{el}+E_{hot}+E_{cold})=0.39$
- $PF_{hot\ (NATURAL\ GAS)}=E_{hot}/(E_{el}+E_{hot}+E_{cold})=0.44$
- $PF_{hot\ (BIOGAS)}=E_{hot}/(E_{el}+E_{hot}+E_{cold})=0.38$
- $PF_{cold\ (NATURAL\ GAS)}=E_{cold}/(E_{el}+E_{hot}+E_{cold})=0.16$
- $PF_{cold\ (BIOGAS)}=E_{cold}/(E_{el}+E_{hot}+E_{cold})=0.23$

$$f = \frac{q^k(q-1)}{q^k-1} \quad (18)$$

$$q = 1 + \frac{r}{100} \quad (19)$$

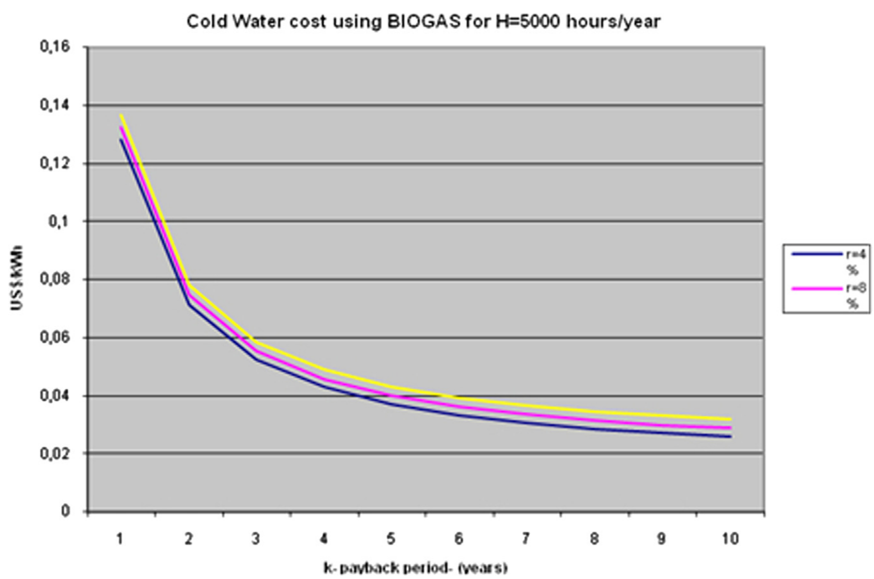


Fig. 23. Cold water cost using biogas for 5000 h/year.

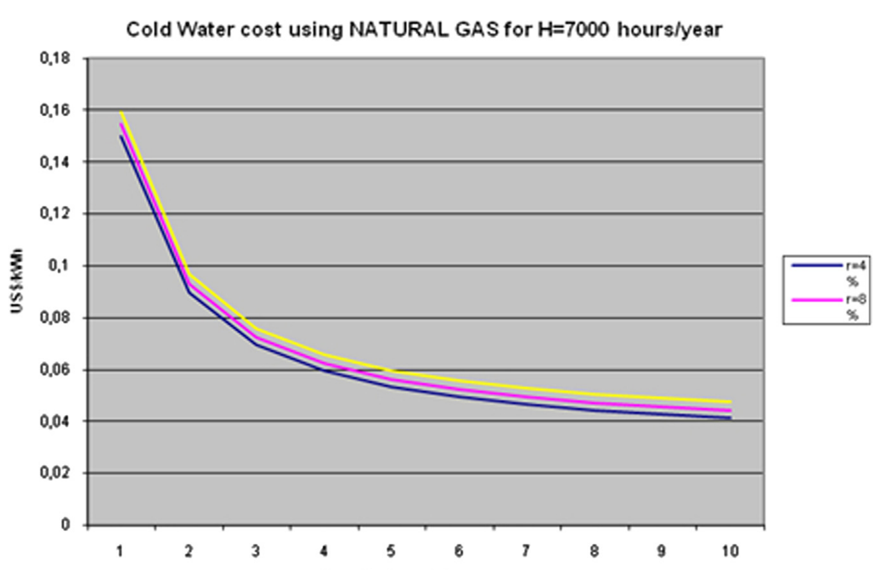


Fig. 24. Cold water cost using natural gas for 7000 h/year.

Exploiting the previous values in Eqs. (15), (16) and (17), diagrams from Figs. 8 to 25 can be obtained.

As it can be seen, concerning a common payback period of 5 years, there are more economical results using biogas as fuel.

Moreover it may be observed that to compete with the Brazilian electricity price ($=0.07$ US$/kWh) it is advisable the cogenerator runs for $H=7000$ h/year, as it can be seen in Figs. 26 and 27.

For what concern hot and cold water production, a better analysis could be done after knowing the final destination of the system, so it will be possible to arrange a comparison between cogeneration production costs and alternative choices ones.

3.2. Comparison to Italian situation

Next it is shown an economic analysis about electricity production utilising the same compact cogeneration system, but considering Italian fuel prices. This effort is done to better understand the differences between South American and European situation and the different economic impact of a system like the one discussed in this work. It is obvious that it is a forced comparison, because in Europe a "stand alone" system is not so required!

It is possible to use Eq. (15) to determine the electricity cost. Capital and maintenance costs are the same, because the system is the same (these are approximations):

- $I_{PM+G}=1200$ US$/kW;
- $C_{MAN(PM+G)}=0.0130$ US$/kWh.

Naturally energetic efficiency is the same:

- $E_{el\ (NATURAL\ GAS)}=12.8$ kW;
- $E_{el\ (BIOGAS)}=12.8$ kW;
- $PF_{el\ (NATURAL\ GAS)}=E_{el}/(E_{el}+E_{hot}+E_{cold})=0.4$;
- $PF_{el\ (BIOGAS)}=E_{el}/(E_{el}+E_{hot}+E_{cold})=0.39$;
- $H=3000$ h/year; 5000 h/year; 7000 h/year.

What changes is fuel cost. In Italy there are differences according to installed powers and consumptions. Considering also

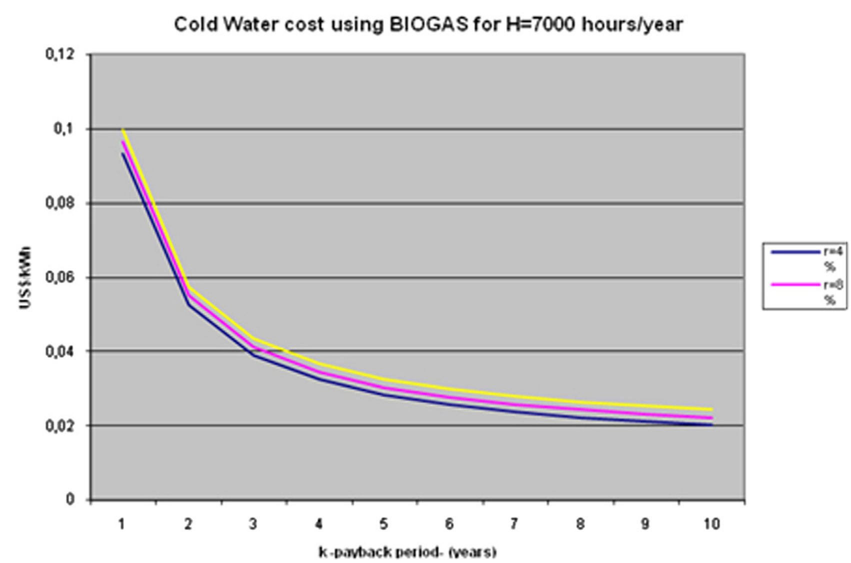


Fig. 25. Cold water cost using biogas for 7000 h/year.

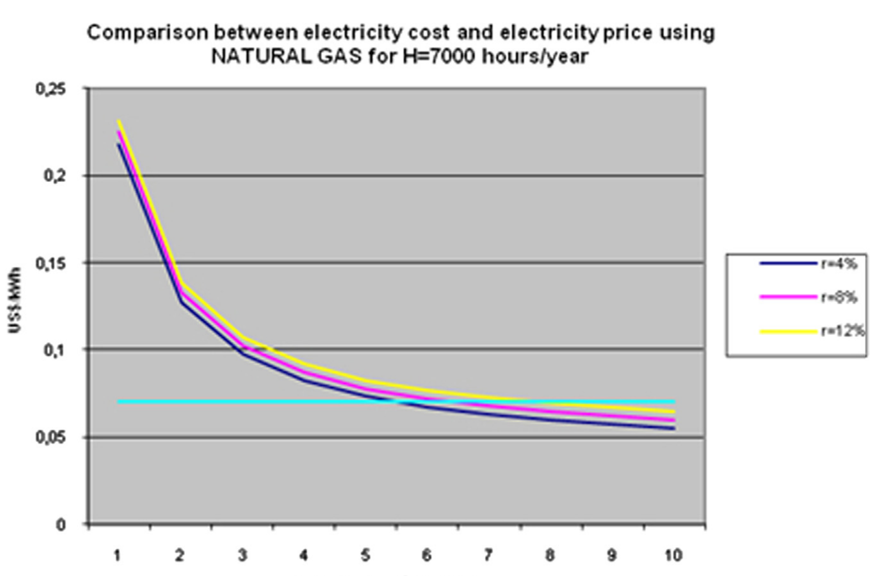


Fig. 26. Comparison between electricity cost and electricity price in Brazil, using natural gas.

taxes, discounts and surcharges, it may be obtained (converting 1 €=1 US$):

- $C_{\text{fuel (NATURAL GAS)}}$ (for $H=3000$)=0.042 US$/kWh;
- $C_{\text{fuel (NATURAL GAS)}}$ (for $H=5000$)=0.04 US$/kWh;
- $C_{\text{fuel (NATURAL GAS)}}$ (for $H=7000$)=0.038 US$/kWh;
- $C_{\text{fuel (BIOGAS)}}$ (for $H=3000$)=0.013 US$/kWh;
- $C_{\text{fuel (BIOGAS)}}$ (for $H=5000$)=0.012 US$/kWh;
- $C_{\text{fuel (BIOGAS)}}$ (for $H=7000$)=0.011 US$/kWh.

Exploiting the previous values Figs. 28 to 33 can be obtained.

Such as the Brazilian case the biogas is more profitable than the natural gas.

In Italy, as guessed, this compact cogeneration system gives more economical results, because the Italian electricity price is higher (=0.16 US$/kWh).

Considering a common payback period of 5 years, this system is rewarding even if the cogenerator runs only for $H=5000$ h/year using natural gas, or for $H=3000$ h/year using biogas, as it can be seen in Figs. 34 and 35.

4. Conclusions

The compact cogeneration system applied in tertiary sector in Brazil is a good technological option. In this country there are many opportunities to use a system like this, since the vastness of the territory prevents the total connection to the national electrical grid and so still remain many isolated areas. Brazil has about 15% of its population (25 million people) without access to dependable electricity supplies. Most of this population has a very low income and lives in rural areas where the costs for installing access to conventional electrification are high [30].

Finally, considering Table 8, the global efficiency of the system shown above results:

$$\eta_{NaturalGas} = \frac{E_{El} + E_{HotWater} + E_{Cold}}{E_{Fuel}} = \frac{12.8 + 12.1 + 1.97 + 5.15}{50.71} = 63.14\%$$

$$\eta_{Biogas} = \frac{E_{El} + E_{HotWater} + E_{Cold}}{E_{Fuel}} = \frac{12.8 + 12.1 + 0.38 + 7.66}{52.29} = 63\%$$

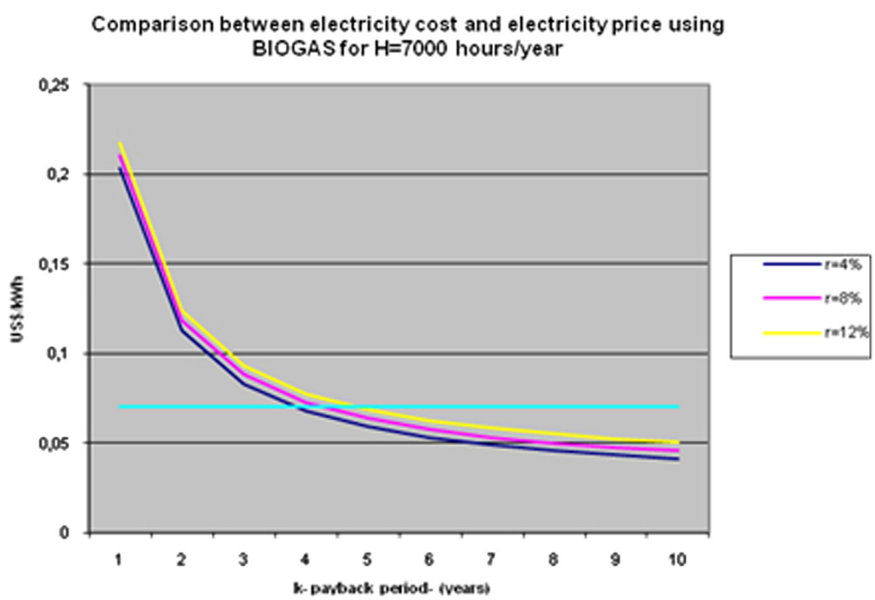


Fig. 27. Comparison between electricity cost and electricity price in Brazil, using biogas.

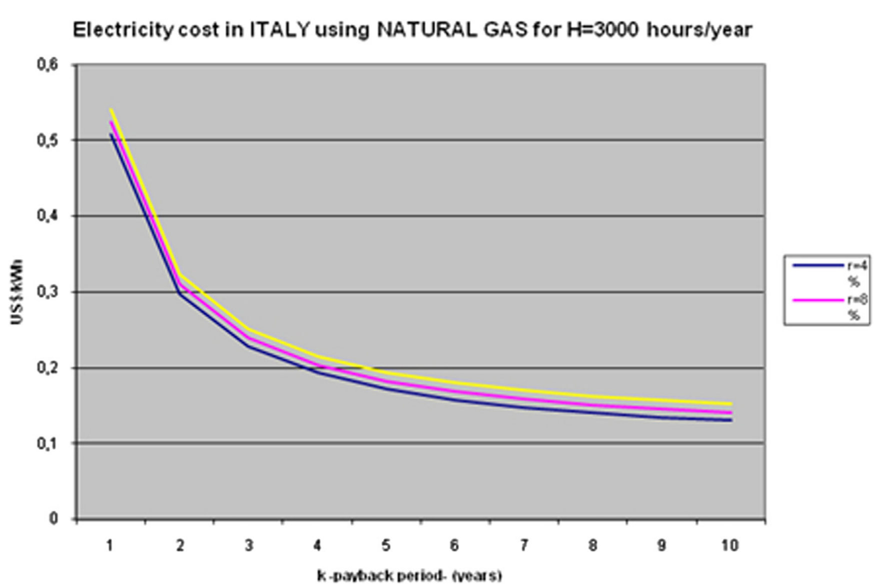


Fig. 28. Electricity cost in Italy using natural gas for 3000 h/year.

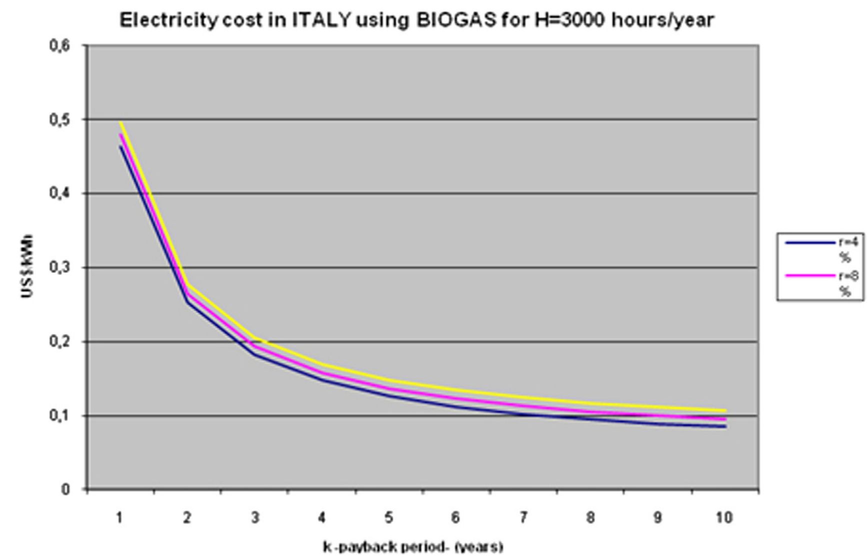


Fig. 29. Electricity cost in Italy using biogas for 3000 h/year.

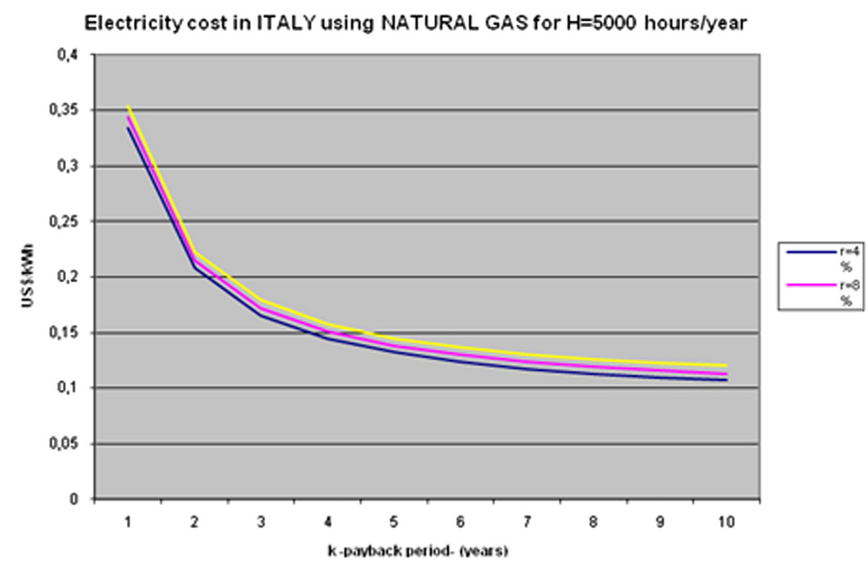


Fig. 30. Electricity cost in Italy using natural gas for 5000 h/year.

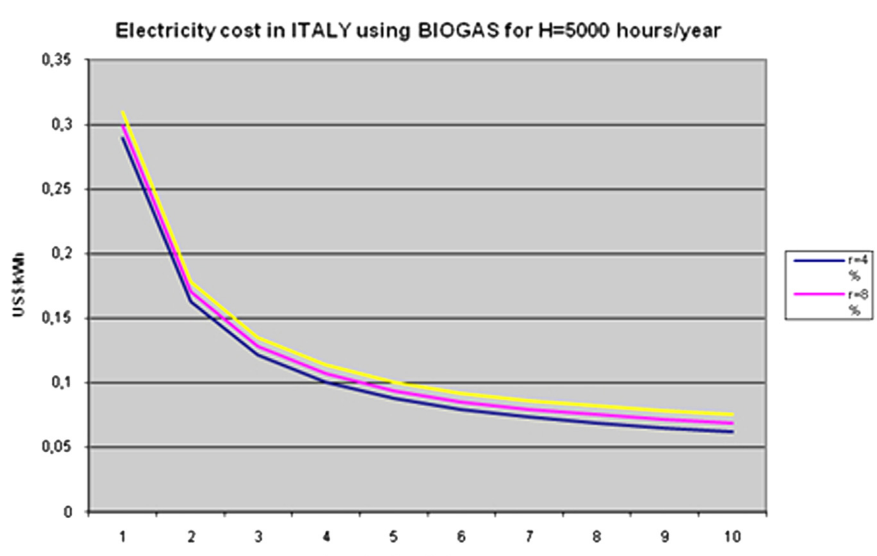


Fig. 31. Electricity cost in Italy using biogas for 5000 h/year.

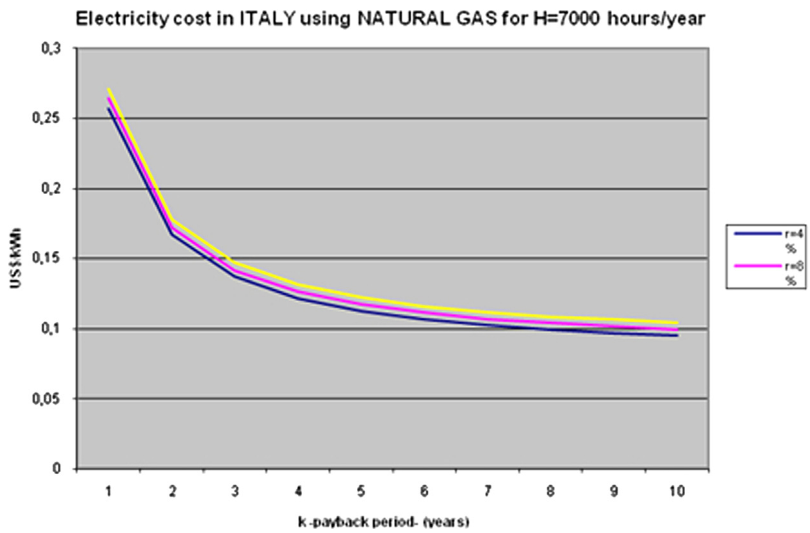


Fig. 32. Electricity cost in Italy using natural gas for 7000 h/year.

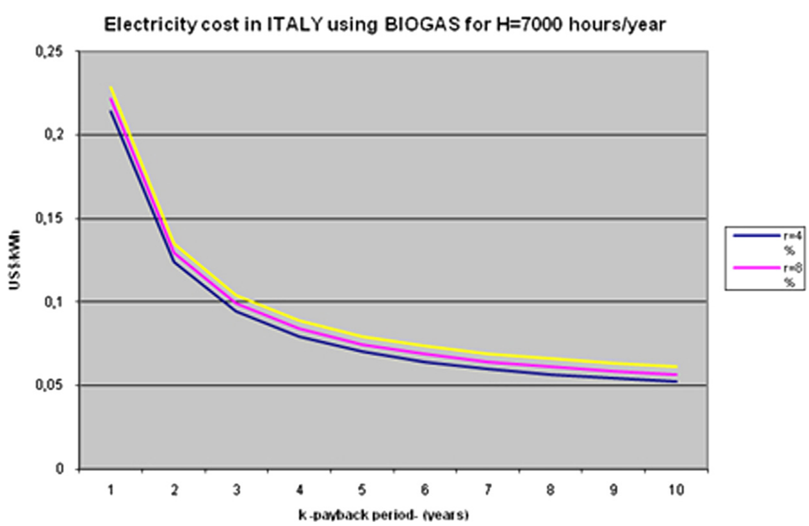


Fig. 33. Electricity cost in Italy using biogas for 7000 h/year.

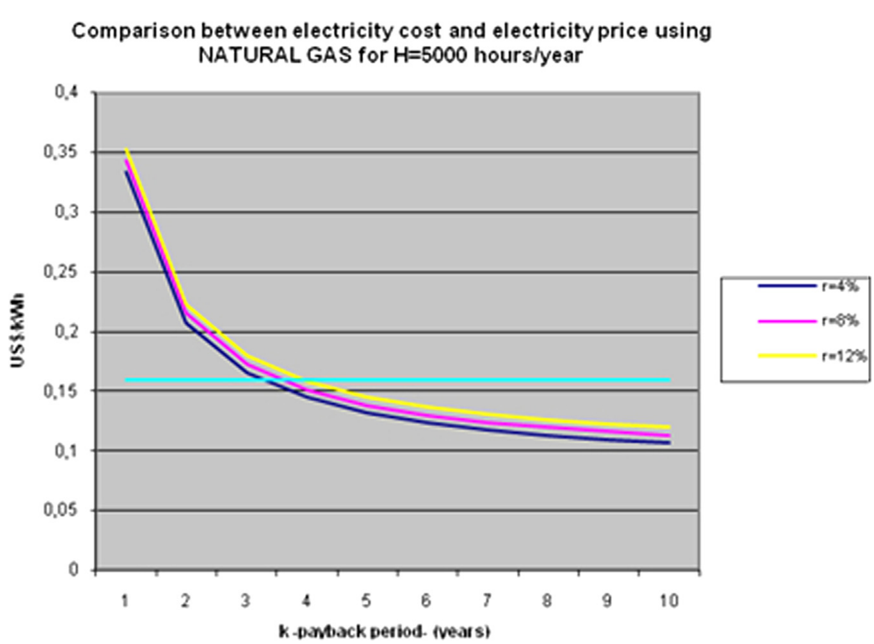


Fig. 34. Comparison between electricity cost and electricity price in Italy, using natural gas.

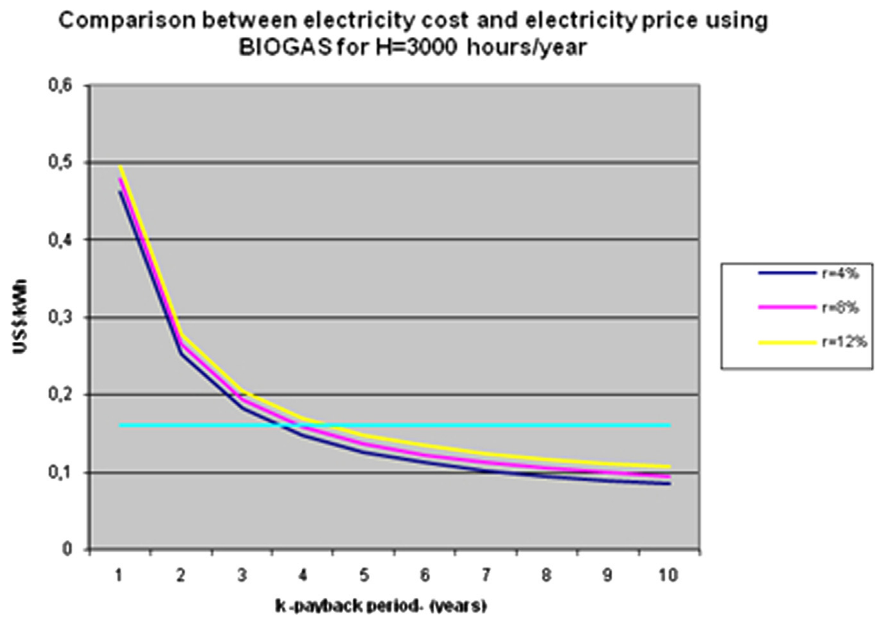


Fig. 35. Comparison between electricity cost and electricity price in Italy, using biogas.

Considering this work, it results that $C_{p\ \text{(NATURAL GAS)}} > C_{p\ \text{(BIOGAS)}}$. Natural gas exchanges more heat with water, and so there is more hot water production using natural gas as fuel than using biogas; on the contrary using biogas more heat remains in the exhaust gases, and so there is more cold water production.

For what concern the economic facet, it's obvious that a complete analysis cannot leave aside the final destination of the system. It will be different if the system will operate in a shopping centre, or in a hospital, or in a school etc.

Generally speaking, concerning a common payback period of 5 years, there are more economical results using biogas as fuel.

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